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NASA Equilibrium

- Game Theory and National Policy -

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After the loss of the Space Shuttle Columbia in February 2003 a new direction began to emerge for NASA in January of 2004 called the Vision for Space Exploration. In November of 2005 NASA released the much awaited Exploration Systems Architecture Study or "ESAS" report. This report presented the case for the new National space transportation architecture for human space flight. This new architecture would include an Apollo-style capsule/service module spacecraft for crew, atop a launcher, the Ares I, derived partly from Shuttle technology, along with a very large cargo-only vehicle, the Ares V, also Shuttle-derived.

This is not the first change in direction for NASA in the past 20 years. Many an announcement has come and gone, and many a project advertising a new direction for NASA, even to the point of building prototypes, have also risen only to fall. Since the mid-90's the stability of NASA programs may best be measured by the time it takes to settle on logos and thence move to coffee cups.

It is the topic of this very short paper to explore an idea – one simple idea. Can the instability in NASA's past, and as likely its present, be understood somewhat by a simple game theory? Is the Federal government one player, industry another, in a prisoners' dilemma of sorts, arriving by virtue of the rules of the game at unstable configurations or sub-optimal equilibriums (short of a Mexican stand-off)?

Further, might exploring this idea lend insight into all players ending at "optimal" equilibriums?

Artists depictions – the proposed Orion Ares I crew vehicle (left) and Ares V cargo vehicle (right)

1. Nash Equilibrium = NASA Equilibrium?

NASA since the 1990's has advanced many an idea on future space transportation. The mosaic below is but a smattering of artist's depictions from past programs. The timing of the large number of studies starting in the early to mid-90's is perhaps a result of the emphasis on the Shuttle in the decade of the 80s, the loss of Challenger, and the push to gain efficiencies in the Shuttle that would focus on an outpost, a space station, well into the 90's. The car was new, then in need of repair, and then the emphasis was what to do with it. Freed by the mid-90's to think about a future space transportation system beyond the Shuttle the race was on to imagine, sell, analyze lessons of the past and otherwise push one strategy over another. Industry players were still aplenty, as major consolidations after the end of the Cold War had not yet stabilized, so the game field could also be characterized as having many players. NASA itself can not at the time, or even today, be considered to be one player, but rather is more realistically thought of as a series of players, in this case as NASA centers around the country.

With this general mind-set about the game a candidate game theory solution concept for NASA could be taken as Nash Equilibrium. [1]Nash equilibrium is a solution concept with a couple of major characteristics – (1) the players know (or believe or assume they know) the other players strategy and (2) no player has anything to gain by acting unilaterally, that is by changing only their strategy given that of the other players.

The table below shows a two-strategy game with two players. Suffice it to consider just 2-players for now, as for the most part our players can be considered as NASA and Industry. The nature of the strategies themselves will be covered ahead. As shown in the table below the players can have the same strategies, but of two different types. The upper left and the lower right quadrants represent a benefit score where strategy B < A, that is it yields less benefit than A to each player if each coordinates with the other. The quadrants in the upper right and lower left (of scores 1,3 and 3,1) are the benefits accrued to that player if they act unilaterally, knowing the other player will act with the alternate strategy.

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[1] John Forbes Nash, Jr. (born June 13, 1928) is an American mathematician and economist whose works in game theory, differential geometry, and partial differential equations have provided insight into the forces that govern chance and events inside complex systems in daily life. From the Wiki on John Forbes Nash @ http://en.wikipedia.org/wiki/John_Forbes_Nash

	Player 2 adopts strategy A	Player 2 adopts strategy B
Player 1 adopts strategy A	4,4	1,3
Player 1 adopts strategy B	3,1	3,3

Suffice it to say that the most benefit accrues to a player individually if both coordinate on strategy A (it was a rule that B < A as regards benefit, even if both form a "cartel" type arrangement and agree to collaborate). Compare the situation of 3,1 and 1,3 benefit as representing where, for example, a standard is not dominant in an industry, confusing consumer sentiment and resulting in less market growth. Consider the "4,4" outcome being an agreed upon standard that grows a market, a standard that is an improvement over standardizing on strategy B. Also observe that both quadrant 4,4 and 3,3 are in equilibrium. Merely knowing that the market for all and the individual benefit of quadrant 4,4 is better than quadrant 3,3 does not incentivize anyone to change "unilaterally" as the benefit ONLY accrues if both parties act in concert.

2. To Reuse or Not to Reuse, is that the Question?

So what does Nash equilibrium possibly tell us about NASA and industry?

In the interest of exploring the possibility that a Nash equilibrium (optimal or sub-optimal) is a *result* of a game between NASA and industry, taking as a given that NASA and industry "believe" they know the equilibrium strategies of the other, and in which each player is also aware that they sink or swim together, *then* it can be assumed that a Nash equilibrium possibly applies. That interesting matter becomes – what is the game? What are the strategies? Can this explain past instabilities in the NASA direction?

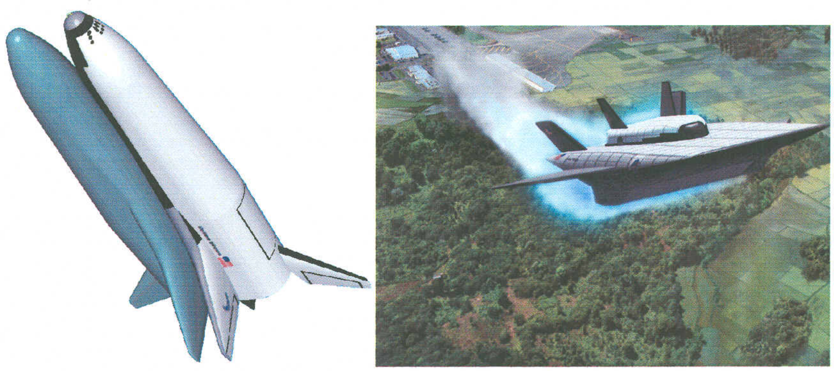
To answer the previous set of questions it's necessary to address individual NASA and industry player strategies. One contrast between the Shuttle, the numerous studies before ESAS, and the ESAS recommended architecture was that each shift had as it's major characteristic either more "reusable" or more "expendable" as a strategy.

The Shuttle was a response post-Apollo to a NASA being told that the day of getting funding equal to 4% of the Gross Domestic Product was over. NASA was heading to being a "1% agency", that is no peak funding that was as large as 4% of the GDP, such a large percent of annual federal expenditures, was to be forthcoming again. With that message clear going into the Nixon administration the Shuttle emphasized an immediate drop in year to year costs for development (resulting in that a cost over-run in development was simply handled as a delay in operational years, that is the planned operational year budgets were simply used to continue development until complete). The longer term goal, to be consistent, was also advertised as meeting some acceptable year-over-year recurring costs (albeit advertising too a productivity, such as 40 flights per year, that was never met). Again, as occurred in development, *the annual cost being the immovable force*, the flight rate was scaled back to match.

In short, the Shuttle derived from players sponsoring a significant shift to reusability. One can presume that because the Shuttle was built and had flown for 30 years that this was an equilibrium point in the game. Had it not been, history would have been different. One can not assume though that it was the "optimal" equilibrium point.

Going to the "decade of studies, studies, studies" – the 1990's saw a host of NASA studies in which only 1 major study (Access to Space Study) even had expendable concepts. NASA had moved in a consensus fashion to reusability after Apollo and it was a given at the time that the next system would build on the Shuttle, on its reusable Orbiter especially.

As event after event showed, the definition of the "next generation" system would go from Access to Space Study, to Highly Reusable Space Transportation study, to X-vehicles (the X-33, the Venture-Star single-stage-to-orbit, the X-34 small reusable launcher, the DC-X vertical take and landing prototype, etc) to the Space Launch Initiative (SLI) program and the Next Generation Launch Technology (NGLT) program. One can assume that all these were unstable equilibrium in that they had short lives, met early demise, or in general failed spectacularly - except as guises under which NASA's development available dollars began to be consolidated and organized. In accordance with failed equilibrium, what opposing strategies were occurring between NASA and industry?



A Couple of Artists Depictions of Reusable's Analyzed and Studied in the NASA "NGLT" Studies

Let us assume for a moment two keywords played into opposing strategies in the 1990's and up to just before the loss of Columbia in 2003, yielding unstable non-equilibrium points in the NASA industry game during those years – *reusable* and *expendable*.

Characteristics of a "reusable" scenario during the 1990's, in retrospect, are truly "disruptive" from the point of view of industry at the time. Regardless of NASA direction towards reusable concepts in study after study the "player 2", here referring to the launch vehicle industry, can be surmised to have a strategy that comes from it's motives and desires, what benefits the industry players individually. Knowing NASA was heading in study after study to "reusable" did not necessarily make Industry entirely follow suit. Recall that in the "game" previously proposed as an explanation framework there are unstable (or very low benefit) quadrants where players do *NOT AGREE* on strategy (quadrants 3,1 and 1,3).

To put this in better perspective – the last reusable orbiter was delivered to NASA in 1991, Endeavour, the replacement ordered by Congress after the loss of Challenger. In effect, there was no "last man standing" to build reusable space-planes after this. The movement by the Department of Defense to build new expendable launch vehicles (the "Evolved" Expendable Launch Vehicle program) only added more incentive for an industry that also serves NASA to push the manufacturing base that had been established vs. taking a risk that a reusable system would go to another competitor.

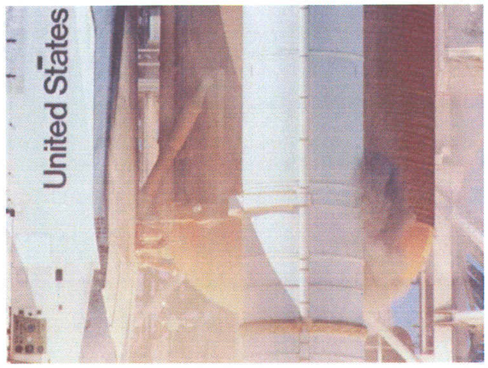
3. Back to Nash Equilibrium

After the loss of Columbia the previous low stability scenarios were once again collapsing. It is enough only to see that a decade and more of studies, prototypes and false-starts ended up scrapped, yielding to a new "study" that would last the next 18 months, to conclude that the configuration of the game between NASA and industry in those times was unstable. Why is another matter. It is proposed here that the driving strategies that bought about the Shuttle were coordinated moves by NASA and industry to align with "reusable". It is further proposed here that the consensus strategy "reusable" collapsed as industry favored "expendable" leading to the unstable period of study after study in the time period 1994-2003. NASA after all was still on "reusable" so a switch by 1 player moved the scenario of the game to what would be quadrants 3,1 or 1,3 of the Nash equilibrium. That is, the collapse of consensus on reusable / expendable caused the instability in this period.

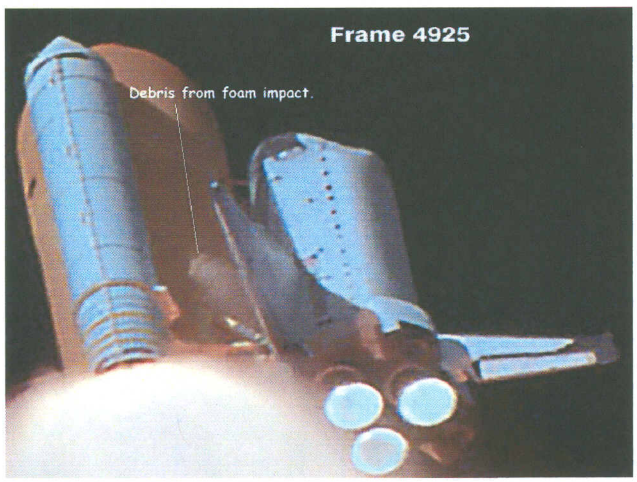
What does this reflect after the loss of Columbia?

Players are driven by an assortment of motives, but Nash equilibrium also speaks to "*immediate*" benefit as perhaps a more likely guide to what each player weights in choosing either to coordinate or to act unilaterally. In addition, the Nash equilibrium only asks that a player say "if I change my strategy, knowing the other's strategies, do I benefit from changing?" If the answer is "yes" forces will eventually arise, incentive exists (the expected benefit) to bring about the change. The player will act.

Consider that going into ESAS the Shuttle had yielded two catastrophic failures. Challenger was a failure of a semi-reusable element, the solid rocket boosters. Similarly, the loss of Columbia was a failure that began with a fully expendable element, the Shuttle External Tank (with debris hitting a fragile orbiter, albeit at a spot more robust than most). How is it possible that amidst previous decades of studying, testing, prototyping and operating reusable systems that a recommended architecture would arise post-Columbia that was not only fully expendable but also based on the parts of the Shuttle that has already taken the lives of two crews? Similarly, how was it possible that the only part of the Shuttle that had not caused a crew loss was summarily discarded going in to the ESAS study, especially given that the emphasis (for a while) after the loss of Columbia was to significantly improve on crew safety?



Smoke at the Solid Rocket Booster (SRB) O-ring seal that would later cause Challengers catastrophic failure



Debris cloud as External Tank (ET) foam, possibly with ice, strikes the left wing of Columbia, leading to later catastrophic failure as Columbia unawares of the damage reentered Earths atmosphere with a damaged wing

Nash equilibrium reflects on these prior questions – in an odd way. The item to consider is not the strategies however, reusable or expendable. It is "who are the players" – that is, it is not possible to affect the Nash equilibrium unless one is a player. One must first join the game to be able to determine an outcome. Here the "strategy" of "reusable" vs. "expendable" can reflect on a second hypothesis. The first hypothesis of applying "equilibrium" thinking to the decades of the 90's as regards NASA and industry is that the players were not in equilibrium. The volatility during these times as regards future space transportation systems is enough to observe to say "this is consistent" – volatility = lack of equilibrium among players. The second hypothesis relating to ESAS is that by this time there was no longer a "reusable" player in the game. That is, there was no player motivated by existing benefits to building future reusable space-planes. NASA centers (such as Marshall Space Flight Center) manage the production of expendable Shuttle hardware, such as boosters and tanks. Contract manufacturers around the country such as ATK Corp. making boosters in Utah, and the Lockheed-Martin contract making tanks in Louisiana at the Michoud Assembly facility (MAF), are also "expendable" manufacturing operations. Further, the largest companies in the sector, Lockheed-Martin and Boeing, have manufacturing capabilities (such as in Dacatur, Alabama) that are focused on expendable vehicle manufacturing.

Put in another context, what would the outcome of ESAS, the direction of the NASA next generation space transportation system have been had there been a continuing "space-plane" (or Shuttle orbiter) manufacturing capability in the country? i.e., a 3rd player.

We return to the Nash equilibrium – substituting A and B for "reusable" and "expendable", and it can be seen that both the lower right and the upper left quadrants on the game board are equilibrium strategies. Essentially, after ESAS, assuming that reusability is long term key to real growth in this space sector, a "sub-optimal" equilibrium point may have been located that is "expendable" (sector where we have "3,3").

	Industry adopts strategy "reusable"	Industry adopts strategy "expendable"
NASA adopts strategy "reusable"	4,4	1,3
NASA adopts strategy "expendable"	3,1	3,3

4. Concluding

Left as is, that is *IF* NASA has given up on "reusable", then the ESAS architecture, or some such "expendable" form (any will do actually to achieve the same equilibrium, it need not be dual, Shuttle derived, etc) is a stable equilibrium, albeit sub-optimal. Nonetheless, to the degree any advocacy in NASA pulls back to some vision of "reuse" then the unstable quadrants are once again "game". Nash equilibrium has been used here to show that the current ESAS "expendable" Shuttle derived architecture was inevitable (in any form, dual, Direct, EELV derived, etc) - in this view as a "simple" Nash equilibrium. This is possibly a result of (a) a *strong* NASA center, MSFC, that benefits from an "expendable" launch vehicle world similar to the "expendable" world today of boosters and tanks, (b) a *neutral* NASA center, Johnson Space Center, that favors neither "reusable" or "expendable" as it has no current manufacturing base to preserve of either kind, (c) a *weak* NASA center, Kennedy Space Center, in that no future reusable manufacturing capability exists, so favoring "reusable" has no immediate benefit and (d) a *strong* industry set of players with standing "expendable" manufacturing capabilities, naturally favoring continuing and building on existing capabilities.

This is how you derive an architecture, ESAS (or any expendable booster and foam-covered tank like system), that is made of precisely the expendable parts that failed and have caused the loss of 14 crew. It's how you discard the part that has served as the fundamental knowledge base for eventually having spaceplanes that routinely take anyone, not just government astronauts, to space and back.

In considering the potential new "expendable" equilibrium (only to the degree its "expendable", the execution itself still open and likely to change due to costs near and far term, by way of one factor) an alternate "benefit" set of scores can be assigned to a simple two-player Nash equilibrium matrix. It could be as follows:

	Industry adopts strategy “reusable”	Industry adopts strategy “expendable”
NASA adopts strategy “reusable”	10,10	1,2
NASA adopts strategy “expendable”	2,1	2,2

Although it’s possible to get “stuck” in the lower right quadrant, and this is a stable solution that by definition resists change, note that the benefit weights to the players, were it to be closer to the above version of the Nash equilibrium table, has a total NASA/Industry “benefit” in the upper left quadrant of 10+10=20 “benefit” points whereas the lower right, also a stagnation/equilibrium point, yields a cumulative benefit to NASA and industry of 2+2=4 “benefit” points. This is just slightly improved than the 2 unstable scenarios at 2+1=3 and 1+2=3 benefit points.

Endless debate can occur about the benefits of reusability, the “benefits” in any quadrant relative to each other, or even the placement of the quadrants in the Nash table. At a given point in time, were a reusable system too difficult, it might be argued to invert the upper left and lower right quadrants of the Nash equilibrium table. Consistent with the original intent of exploring instability within the realm of game theory, and of critiquing the nature of any NASA equilibrium state (sub or optimal), such a perspective would be valid. Nonetheless, the view presented in this analysis is about the broad sweep of technological advance in a transportation industry. Since no examples exist anywhere in human history where complex infrastructure relates to wide-spread growth, routine operations, and costs and safety accessible to broad swaths of society, while also being expendable, disposable or otherwise “one use only”, the benefit quadrants and notional weights are as presented. The first airplanes or cars, technological devices of some complexity for the time, may rightly be called “fractionally” expendable, given lack of robustness, or expensive, regular “re-build” needs. Yet it was only as true reusability was achieved that these industries took on the growth characteristics and benefits that would dwarf all previous notions of doing well in the industry.

It is left to further study to determine more precisely actual benefits as well as how to escape from the sub-optimal stagnation point for NASA and industry represented in the quadrant “2,2”. The “expendable” equilibrium point may have a “benefit” scale that contrasts more favorably with the optimal solution even as a sub-optimal equilibrium. For example, the “expendable” point may be a set of elements or advanced supplier processes that lend themselves to low cost manufacturing and ease of integration and launch. The sub-optimal equilibrium points stability is likely enhanced to the degree it moves toward greater efficiency and productivity (for reasons of not introducing or affecting other players, who in turn may act unilaterally). In addition, the introduction of new players, or the passions of safer, more accessible, more routine, more affordable space transportation advocates can de-stabilize the existing post-Columbia equilibrium (these advocates would, however, have to be “players” rather than just “mattress mice”). The former “new players” could be from outside the current mainstream (commercial orbital transportation services for example) whereas the later “new players” may come from within.

5. Caveat, on the use of the Word "Game"

Space is not a game. Space is a serious business. The use of the term "game" in this paper is merely the terminology of understanding players, strategies and outcomes, with a smattering of motive to boot. It is the terminology used to understand the behavior of parties in economic arrangements, in combative situations of war or avoiding war, and in industry competing and acting within markets.

It is not used here to trivialize the business of space. The decisions upon us are serious and far reaching. Our decisions and our drives affect human lives, directly as crew safety, and indirectly in people's livelihoods and our National economic health.

About the Author

Mr. Zapata has worked with NASA at the Kennedy Space Center since 1988. In that time he has held responsibility for Shuttle systems including the Shuttle External Tank and the Shuttle cryogenic propellant loading systems, as related flight and ground propulsion systems. Starting in the mid 90's he began work to translate the operations experience into improvements in flight and ground system designs for achieving improvements in ground operations processing from landing through launch, in all aspects from direct to in-direct operations. He participated in the Explorations Systems Architecture Study or "ESAS" contributing launch and landing ground operations cost estimates and integrating the KSC cost estimates into the ESAS life-cycle cost analysis.

Most recently Mr. Zapata is performing (1) strategic Constellation and NASA agency level future scenario analysis and (2) analysis supporting the Constellation Standing Review Board, by providing independent analysis of the KSC ground operations project.

Mr. Zapata looks forward to the day when access to space is safe, routine and affordable as a result of taking advantage of, quantifying and understanding the experience and lessons of past and current space transportation systems operations.

For related material see: http://science.ksc.nasa.gov/shuttle/nexgen/rlvhp.htm